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TECHNICAL REPORT
CP-5

FC
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COMPOSITE PERSONNEL ARMOR

QUARTERMASTER RESEARCH & DEVELOPMENT CENTER
CHEMICALS & PLASTICS DIVISION

58AA 5673

DECEMBER 1957 NATICK, MASSACHUSETTS

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QUARTERMASTER RESEARCH & ENGINEERING COMMAND, US ARMY
OFFICE OF THE COMMANDING GENERAL
NATICK, MASSACHUSETTS

Major General Andrew T. McNamara
The Quartermaster General
Washington 25, D. C.

Dear General McNamara:

This report, "Composite Personnel Armor," presents results of an exploratory study of the ballistic properties of materials. Significant findings of this investigation, using the .22 caliber 17 grain fragment simulating projectile, are as follows:

> A composite structure of titanium and nylon cloth was found to be superior to any known single armor material.
>
> A significant synergistic effect was noted when a material with a high stopping power was combined with a material possessing high energy absorption. A method of selecting components for a synergistic composite that is better than any single component was suggested by the use of ballistic limits data and missile residual velocity data.
>
> Unusual missile-retarding characteristics were observed for titanium A-110AT and polymethyl methacrylate sheet. The energy absorption characteristics of glass previously reported were verified.

Consideration of these findings indicates that proper exploitation of these phenomena can achieve significant improvements in personnel armor.

Sincerely,

C G Calloway

C. G. CALLOWAY
Major General, USA
Commanding

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HEADQUARTERS QUARTERMASTER RESEARCH & ENGINEERING COMMAND, US ARMY
Quartermaster Research & Engineering Center
Natick, Massachusetts

CHEMICALS & PLASTICS DIVISION

Technical Report
CP-5

COMPOSITE PERSONNEL ARMOR

Anthony L. Alesi

Protective Materiel Branch

Project Reference:
7-80-05-001

December 1957

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FOREWORD

During World War II, a major advance in personnel protection was made by the introduction of Doron (a polyester-glass fabric laminate) and nylon cloth (as cloth or as a resin-bonded laminate). Since that time, no significant progress has been made in providing the combat soldier with armor which he can wear and which affords greater protection against battlefield missiles than the armor now available.

The work described herein is of an exploratory nature. Its purpose was to determine whether or not combinations of materials can provide more protection than single armor materials. The favorable results from these exploratory tests enhance the prospects for development of better armor with materials now available through the use of composite structures.

GEORGE R. THOMAS, Ph.D.
Chief
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Approved:

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A. STUART HUNTER, Ph.D.
Scientific Director
QM Research and Engineering Command

CONTENTS

ABSTRACT

The concept that composite armor, consisting of two or more dissimilar materials, is capable of producing substantially greater protection than an equivalent weight per unit area of any one component was studied. The results of exploratory experiments with the .22 caliber 17 grain T37 fragment simulating projectile, demonstrating the synergistic effect obtainable with composite armor, are given for three systems of two components each.

Measures of the ability to "defeat" missiles (such as the V_{50} ballistic resistance limit) and to retard missiles are presented as guides for the selection and positioning of components within a composite. Data on residual velocity as a function of missile striking velocity obtained with the .22 caliber 17 grain T37 fragment simulating projectile for 5 materials (nylon cloth, titanium A-110AT, aluminum 2024T3, glass and polymethyl methacrylate) are presented. By the application of this concept of composite armor, significant advances are anticipated in providing protection against battlefield missiles for personnel.

COMPOSITE PERSONNEL ARMOR

INTRODUCTION

The selection of materials for lightweight armor has, in the past, been based on the ability of the armor to "defeat" a test missile, i.e., prevent the missile from passing through the armor and causing injury or damage to the target behind the armor. The "stopping ability" of the armor is usually measured by one of three factors:

1. The number or percentages of impacts wherein complete penetration of the armor occurred.

2. The maximum velocity of the test missile at which no penetration or a certain percentage of complete penetrations result (e.g., V_{50} for 50 per cent probability of penetration).

3. In terms of a weight ratio, comparing a material with the weight of a "standard material" having the same stopping ability.

The selection of materials for armor usually has involved the choice of a single material rather than a combination of materials. When two materials have been used, the reason has been to obtain advantages not related to the protective characteristics, e.g., the use of a plastic liner with the M-1 steel helmet in order to have a separate piece of lightweight headgear. When two armor materials are used together, the resultant protective characteristics of the composite have been intermediate between those of an equivalent weight/unit area of each material. The expression $V_{50} = \sqrt{V_{50}^2{}_{(1)} + V_{50}^2{}_{(2)}}$ has been used* to approximate the V_{50} ballistic resistance limit of a two-component armor. The use of this expression for combinations of layers of nylon fabric has been justified by Rogers[1] from an analysis of V_{50} ballistic resistance limits data.

The first indication that there were important factors other than "stopping ability" came in 1945. As certain experiments were designed to make Doron (a resin-bonded, glass-fabric laminate developed by the Quartermaster Corps during World War II) provide protection against small arms fire by using structures in front of the Doron to mushroom, yaw, deflect or break up the bullet, glass sheet, a readily obtainable and very hard material, was suggested. When glass-faced Doron was tested, it was found by Webster[2] that this combination of materials was more effective than Doron, glass, Hadfield steel or a Hadfield steel-Doron combination in defeating carbine and rifle bullets (i.e., a significantly lower weight of the composite was needed than for either of the single materials). Mellecker and Gailus,[3] then conducting work on the development of Doron armor under QMC contract, were led by

*By Watertown (Mass.) Arsenal.

Webster's findings to study the missile-energy absorbing characteristics of glass. They found that test missiles penetrating a pane of window glass backed by Plasticene (artists' modeling clay), all stopped at approximately the same depth in the clay regardless of the initial velocity of the missile. Missiles fired at 1200, 1600 and 1900 ft /sec. all penetrated to a depth of about five centimeters. Prior experience had shown that each centimeter of penetration beyond one centimeter indicated 20 ft /sec residual velocity. They also noted deformation of the hardened steel missile, a yawed dart hardened to Rockwell C42. Further experimentation with a 7/32-inch steel sphere, with clay penetration as the criterion of residual velocity, showed that the velocity loss of the missile was almost as large as the striking velocity, and that it increased directly proportional with increasing striking velocity. However, for duraluminum (typical of many armor materials, including steel and Doron), the velocity loss of the missile increased only slightly with increasing striking velocity and tended to approach a constant value.

During 1947-1950, the Midwest Research Institute, under contract to the Ordnance Corps, studied the numerous factors involved in the general problem of designing body armor to provide maximum resistance to penetration of munition fragments.(4,5) The performance of armor materials was defined by the projectile residual velocity vs. striking velocity relationship. This relationship could be used to predict the performance of composite armor. For example, it was predicted that a hypothetical 2024-T3 aluminum-nylon cloth composite would be superior to either component in stopping fragments. It was reported that composites of these two materials, particularly at higher velocities, were found to be less effective than predicted in reducing the velocity of penetrating missiles.

Another Ordnance contractor, Battelle Memorial Institute, found that, as increasing amounts of aluminum or stainless steel cloth were substituted for nylon cloth, progressively lower ballistic values for the composite were obtained.(6)

The Aberdeen Proving Ground has determined the residual velocities of projectiles after penetration through armor and has used such data in evaluating the effectiveness of armor materials in terms of estimates of casualty ratios.(7)

In 1953, Weinberger and Delcellier(8) reported that the ballistic resistance of fabric armor could be increased by a combination of fabrics which took maximum advantage of each fabric's behavior at different velocity levels. A practical application of this finding was the use of both nylon and Fortisan fabrics in the Canadian armor vest. Also, in 1953, Weiner(9) reported that an improvement in ballistic resistance limit was obtained by selecting, for the front layers of a fabric armor structure, a fabric highly resistant to shear and, for the rear layers, a fabric of high resistance to yarn slippage.

In 1955, consideration of (a) the energy absorption characteristics of glass as reported by Mellecker and Gailus, (b) the greater effectiveness of glass-faced Doron armor compared to single armor materials and (c) the greater effectiveness of fabric composites compared to a single fabric, led to the concept being presented by this report: that composite armor through proper selection and combination of components would provide significantly greater protection than any single armor material. Selection and combination of components are based on consideration of both the stopping power (for example, as expressed by a V_{50} ballistic limit) and the ability of the material to reduce the kinetic energy of the missile as it passes through it. The front component(s) is selected from high energy absorbing materials to reduce the initial high velocity of the missile, while the rear component(s) is selected from high stopping power materials to defeat the missile. In such a combination, each material would be brought into operation at the velocity range where it was most effective.

To test this concept, the exploratory investigation described here was conducted in 1956 with the following objectives:

a. To verify the remarkable energy absorption characteristics of glass claimed by Mellecker and Gailus[3] (using yawed dart and steel sphere missiles and with clay penetration as an index of residual velocity). This investigation used a .22 caliber T37 fragment simulating projectile and made direct measurement of the missile's residual velocity.

b. To determine whether a few arbitrarily selected combinations of materials exhibited any synergistic effects in providing protection against missiles.

c. To determine the energy absorption characteristics of a few armor materials using as an index the velocity loss of the missile in passing through the material.

EXPERIMENTAL METHODS

Two measures of a material's effectiveness in providing protection against missiles were determined.

The first measure is the conventional V_{50} ballistic (protection) limit which measures stopping power. The velocity of attacking missiles is determined at which the probability exists that fifty per cent of the missiles pass through the target and through a witness plate of 2024-T4 aluminum placed six inches behind the target. The procedure and equipment for making the V_{50} limit determination is identical to that used for the testing of lightweight armor materials or items.[10,11] The customary lumiline screen-chronograph-counter system was utilized to measure missile velocity. The missile used in all cases was the 17 grain .22 caliber T37 fragment simulator.[12]

The second measure of a material's effectiveness in providing protection against missiles is the velocity of the missile after it has passed through the armor material. This residual velocity was determined by using a second set of screens (connected with another set of counter chronographs) behind the target. The diagram (Figure 1) shows this equipment arrangement. Whenever the target material shattered and spattered particles back toward the rear screens, a material of low resistance to entrap or "filter out" these particles was used in order to eliminate the possibility of particles triggering the screens. Correction for the velocity loss incurred by the projectiles in passing through the "filter" was made from velocity loss curves previously determined. The correction never exceeded 140 feet per second and was usually less than 100 feet per second.

At velocities substantially below 1000 feet per second, paper screens printed with a silver grid were used instead of the lumiline screens. Also, a gun actuated by compressed helium was used. This gun and equipment was designed and built by personnel of the Biophysics Division, Directorate of Medical Research, Army Chemical Center, Md.[13]

Three armor composites of two components each and five materials were tested. The V_{50} ballistic limit of a window glass-nylon cloth composite was determined in order to ascertain quickly whether or not the previously reported energy absorption properties of glass would be apparent when tested with the .22 caliber fragment simulator. A V_{50} limit much higher than would be expected from the equation $V_{50}\ \text{composite} = \sqrt{V_{50}^2(1) + V_{50}^2(2)}$ would indicate that the glass component had absorbed a significant amount of energy from the attacking missile. If a high V_{50} limit was obtained, verification of the energy absorption effect would be made by measurement of the residual velocity of missiles passing through glass. The V_{50} ballistic limits of two other composites, a titanium alloy A-110AT backed with nylon cloth and a polymethyl methacrylate sheet backed with polyvinyl butyral were also determined in an attempt to demonstrate that materials other than glass also exhibited a synergistic effect when properly combined.

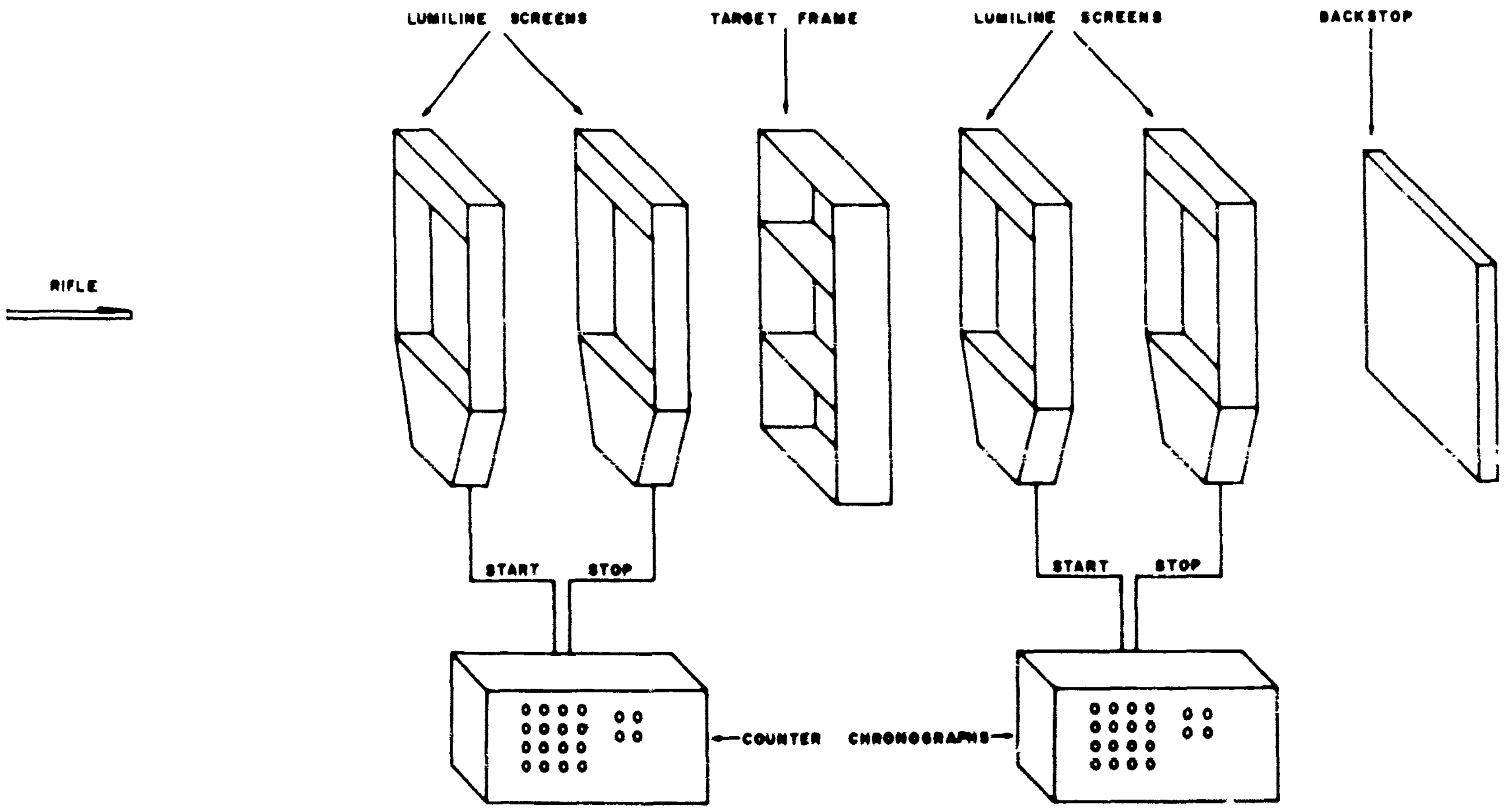


Figure 1 - Arrangement of velocity-measuring equipment

The total weight of the composite was selected to be approximately 40 ounces per square foot (areal density of M-1 helmet plus liner). The ratio of the two components was determined by the availability of the rigid components.

RESULTS

V_{50} Ballistic Resistance Limits

The V_{50} ballistic limits of a composite of window glass backed with nylon fabric[11] and the V_{50} limits of the two components are shown in Table I and are compared at the composite areal density (41.7 oz/sq ft) with equivalent nylon fabric and glass. The comparison with glass is made on the basis of an estimated V_{50} limit for 41.7 oz/sq ft glass calculated by interpolation of missile velocity loss data for 23.0 and 49.2 oz/sq ft glass and from the V_{50} limit for 23.0 oz/sq ft glass.

TABLE I. V_{50} Ballistic Resistance Limits of Composite of Window Glass Backed With Nylon Fabric and of the 2 Components

Material	Areal Density (oz/sq ft)	V_{50} Limit (Protection)
Window glass, 3/32 inch thick	23.0	392[a]
Nylon cloth, 14 oz/sq yd 12 plies, MIL-C-12369	18.7	1280[b]
Window glass and nylon cloth composite		
Observed	41.7	1750
Calculated[c]		1339
(Difference between observed and calculated values		411)
Equivalent weight of nylon cloth	41.7	1770[b]
Equivalent weight of glass	41.7	760[d]

(a) See Reference (14); (b) See Reference (15); (c) The V_{50} of two components is equal to the square root of the sum of the squares of the V_{50}'s of each component; (d) Estimated.

It is apparent that glass in combination with nylon armor cloth, is as effective in stopping the .22 caliber fragment simulator as an equivalent weight of nylon armor cloth. In effect, glass, usually not considered as an armor material, becomes the equivalent of nylon armor cloth when combined with that cloth. Also, as shown in the table, the V_{50} limit experimentally determined for the glass-nylon cloth combination is 31 percent greater (411 ft/sec) than the calculated limit. Therefore, glass must be considered as possessing unusual energy absorption characteristics.

The second two-component system tested in an attempt to demonstrate the synergistic effect of composite armor consisted of a titanium alloy and nylon fabric assembly. The titanium alloy, A-110AT, containing aluminum and tin, was selected when it was observed that this material deformed impacting missiles. Deformation of missiles had also been observed in the case of glass. It should be noted that the missiles are hardened steel (Rockwell C30). A 0.063-inch thick sheet of A-110AT titanium alloy, in the hot rolled annealed condition, was placed in front of eight plies of nylon armor fabric. The test results for this combination are shown in Table II and are compared to an equivalent weight (36.9 oz/sq ft) of nylon armor fabric and of the titanium alloy. The V_{50} limit for 36.9 oz/sq ft of titanium A-110AT was estimated from energy absorption data for 24.0 oz/sq ft material.[14]

TABLE II. V_{50} Ballistic Resistance Limits of Composite of Titanium Alloy A-110AT Backed with 8 Plies of Nylon Cloth and of the 2 Components

Material	Areal Density (oz/sq ft)	V_{50} Limit (Protection)
Titanium alloy, A-110AT, 0.063 inch thick	24.5	1200
Nylon cloth, 14 oz/sq ft 8 plies, MIL-C-12369	12.4	1121[a]
Titanium alloy and nylon cloth composite		
Observed	36.9	1831
Calculated[b]		1642
(Difference between observed and calculated values		189)
Equivalent weight of nylon cloth	36.9	1675[c]
Equivalent weight of A-110AT	36.9	1750[d]

(a)See Reference (16); (b) The V_{50} of two components is equal to the square root of the sum of the squares of the V_{50}'s of each component; (c) See Reference (15); (d) Estimated-See Reference (14).

It is noted that the combination of titanium and nylon armor cloth has superior protective characteristics compared to an equivalent weight of either component and also, for the first time, the ballistic resistance limit of nylon armor cloth has been exceeded. As shown in Table II, the V_{50} limit of this combination was determined to be 156 ft/sec greater than that of an equal weight of nylon armor cloth and is 189 ft/sec greater than the calculated V_{50} limit for this combination. A synergistic effect is also considered to be operative in this case.

A third example of the synergistic effects of combinations of armor materials was found in the transparent armor structures developed for mine clearance armor. These consist of three components laminated together:

a. A polymethyl methacrylate sheet, 3/8 inch in thickness.

b. An interlayer consisting of five layers, 0.015 inch per layer, of safety glass grade polyvinyl butyral.

c. A backing film of 0.003 inch thick nylon (to retain shattered fragments of polymethyl methacrylate which may act as secondary missiles).

For the effects discussed, the influence of the backing film is negligible because of its thinness and its low density and can be disregarded. Table III shows the V_{50} limits of the two major components and of the composite.

Table III. V_{50} Ballistic Resistance Limits of Polymethyl Methacrylate and 5 Layers of Polyvinyl Butyral and its 2 Components

Material	Areal Density (oz/sq ft)	V_{50} Limit (Protection)
Polymethyl methacrylate sheet, 3/8 inch thick	35.7	920
Polyvinyl butyral, five layers, each 0.015 inch thick	6.8	410
Transparent armor structure		
Observed	42.5	1550
Calculated*		1042
(Difference between observed and calculated values		508)
Equivalent weight of polymethyl methacrylate sheet	42.5	1025
Equivalent weight of polyvinyl butyral sheet	42.5	870

*The V_{50} of two components is equal to the square root of the sum of the squares of the V_{50}'s of each component.

This combination of two plastic materials, polymethyl methacrylate and polyvinyl butyral, quite different in physical make-up from the glass-nylon fabric and the titanium-nylon fabric combinations, also exhibits unusual energy absorption characteristics. The difference between observed and calculated V_{50} limits for the transparent armor structure is approximately 500 ft/sec. The differences between the V_{50} limit for the composite structure and an equivalent weight of either the polymethyl methacrylate sheet or polyvinyl butyral sheet is also large, approximately 500 and 700 ft/sec., respectively. It is interesting to note, however, that no deformation of the missile occurs with this combination of plastics.

Residual Velocity Results

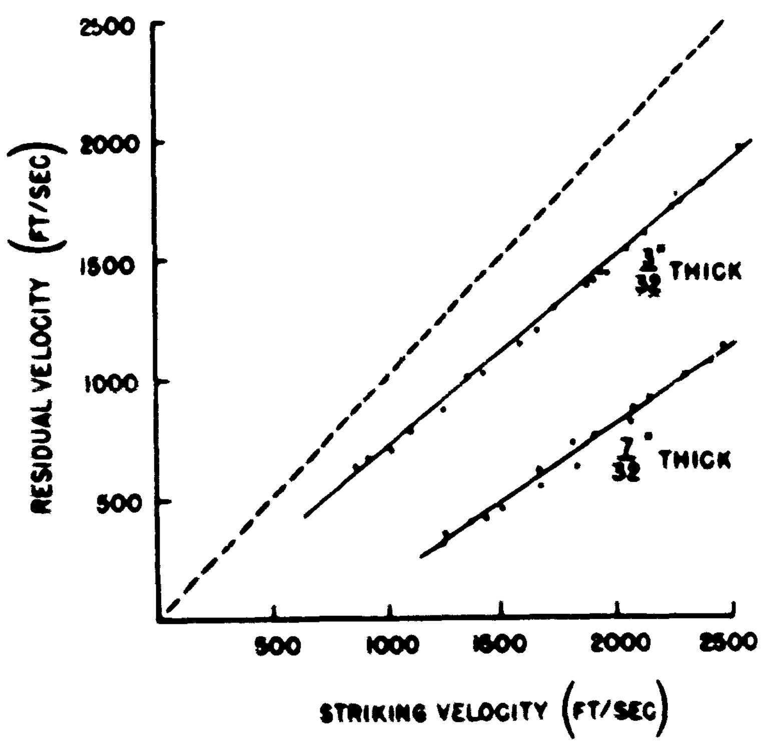
The energy absorption characteristics of several materials, including glass, metals, fabrics and plastics, were determined. Figures 2 through 6 show the results plotted as missile residual velocity against missile striking velocity. The relationships shown were calculated by the method of least squares.

Window glass, 3/32 and 7/32-inch thick, was tested in the range of striking velocities from 700 to 2500 ft./sec. The significant fact, as shown by Figure 2, is that the difference between the striking velocity and the residual velocity (that is, the loss in velocity of the missile) increases as the velocity increases, thereby confirming the conclusion of earlier workers.(3) For materials such as aluminum, steel, and nylon armor cloth, it has been found(3,14) that this missile velocity loss diminishes slowly with increasing velocity and approaches a limiting value. The difference between striking velocity and residual velocity is represented by the vertical distance between the curve and the 45° line (residual velocity = striking velocity) of Figure 2. The effectiveness of a material in reducing the energy of the impacting missile is indicated by the distance of the curve below the 45° line and by its slope. The lower the curve and the closer it approaches the horizontal, the more effective is the armor material that the curve represents. The slope of the curve indicates how rapidly the difference changes with velocity. For conventional materials, the slope approaches unity. For 3/32-inch glass, the slope is 0.79. For 7/32-inch glass, the slope is 0.65, appreciably less than that of the thinner glass. Consequently, it appears that the effectiveness of glass as an energy absorber increases with increasing thickness.

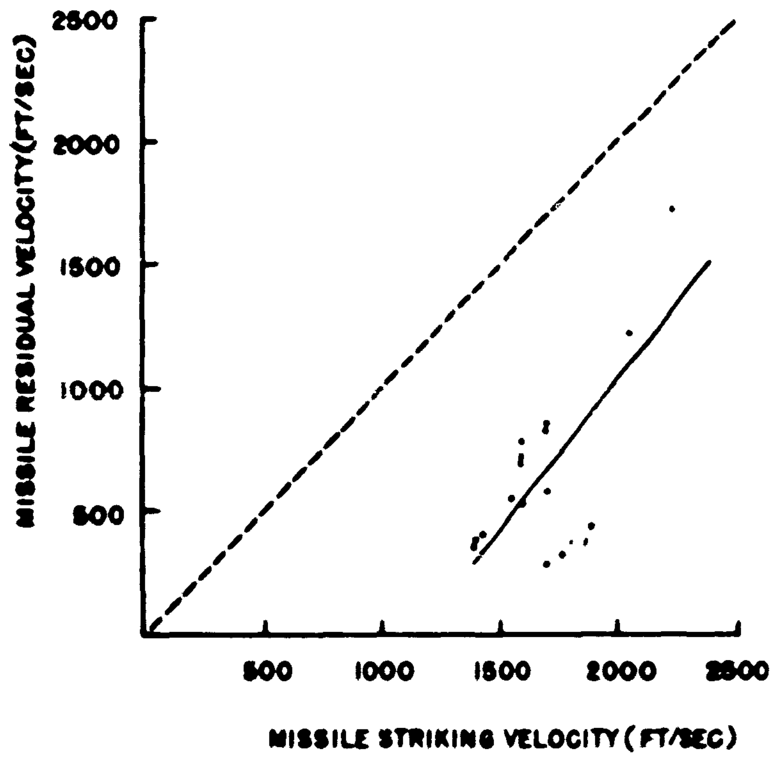
The residual velocity-striking velocity relationships of missiles penetrating A-110AT titanium alloy are shown in Figure 3. The line shown is displaced a considerable distance from the 45° reference line at the lower striking velocities but is closer at the higher velocities. The extent of the displacement from the 45° reference line indicates a high capacity for energy absorption; the slope (1.22) indicates that this capacity decreases with increasing velocity. The latter indication is questionable because of the high degree of scatter in the data and insufficient number of points at the higher velocities.

Figure 4 shows the residual velocity-striking velocity relationship for missiles penetrating nylon cloth. This curve rapidly approaches the 45° reference line asymptotically, and is considered to be typical of materials that are poor energy absorbers when impacted by missiles travelling at velocities much above the ballistic limit.

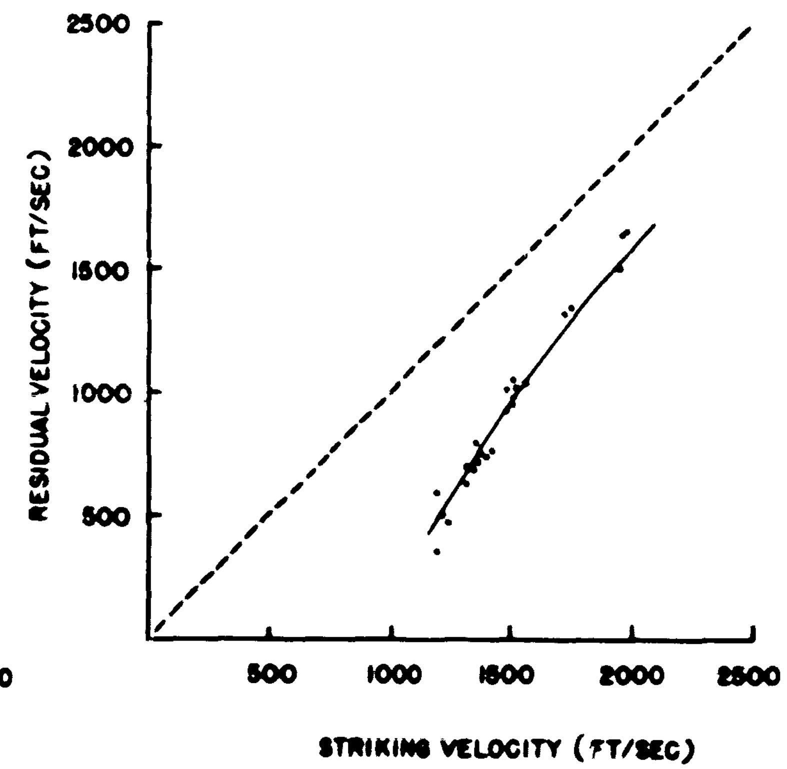
MISSILE RESIDUAL VELOCITY-STRIKING VELOCITY RELATIONSHIPS
(.22 caliber, 17-grain, T37 fragment simulating projectile at 0° obliquity)



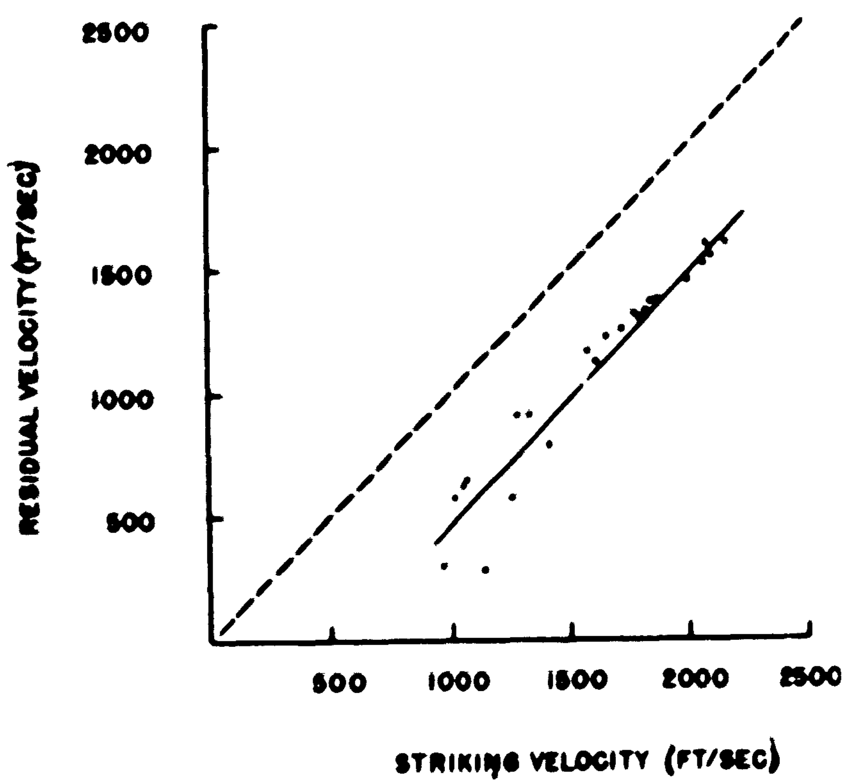
2. Glass -- 3/32", 23.0 oz/sq ft and 7/32", 49.2 oz/sq ft



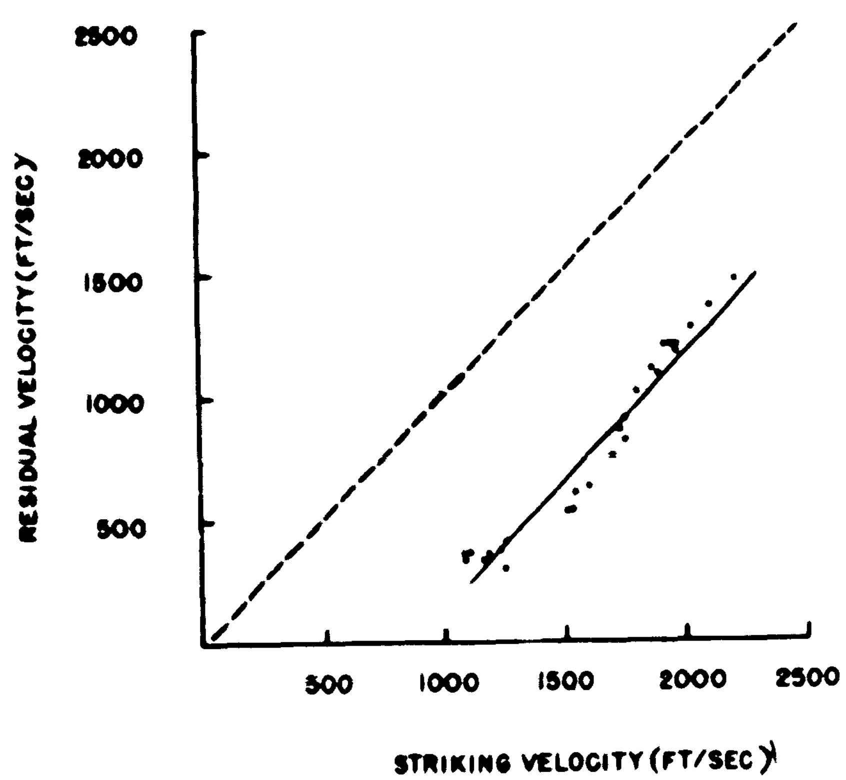
3. Titanium alloy A110AT, 0.063", 24.5 oz/sq ft



4. 12-ply cloth, nylon, armor, MIL-C-12369, 18.7 oz/sq ft



5. Aluminum alloy 2024-T3, 1/8", 29.5 oz/sq ft



6. Polymethyl methacrylate, 3/8", 35.7 oz/sq ft

The data for 1/8-inch thick 2024-T3 aluminum (formerly designated 24S-T300) are shown in Figure 5, as a straight line approximately parallel (slope 1.02) to the 45° line. A straight line with a slope of unity is considered to be typical of metals.

The residual velocity-striking velocity data obtained with 3/8-inch polymethyl methacrylate sheet (35.7 oz/sq ft) are shown in Figure 6. The straight line for polymethyl methacrylate sheet is displaceda considerable distance from the 45° reference line. The slopeof the line is 1.03.

Comparison of Figures 2 through 6 shows that the velocity loss of the .22 caliber T37 fragment simulator in passing through armor is dependent upon the material and upon the areal density of the armor. Materials of different types appear to differ greatly in reducing the velocity of this particular missile. A comparison of the data for two thicknesses of glass shows that the velocity loss/arealdensity ratio is greater for the thicker glass throughout the range of striking velocities. For both thicknesses, the velocity loss/areal density ratio is greater at the higher than at the lower velocities. Table IV shows this ratio at two striking velocities. Table IV also shows that the velocity loss/weight ratio is less at the higher velocity for titanium A-110AT and nylon cloth, but is constant for the aluminum alloy and for polymethyl methacrylate. Titanium A-110AT has a much higher velocity loss/weight ratio at both the velocities shown than any of the materials. However, at lower velocities than shown here, nylon cloth is expected to have a ratio approaching that of titanium A-110AT.

TABLE IV. Ratio of Velocity Loss (ft/sec) to Areal Density (oz/sq ft)

Material	Weight (oz/sq ft)	Missile Striking Velocity 1500 ft/sec	2000 ft/sec
Glass, 3/32"	23	17.0	21.7
Glass, 7/32"	49.2	20.5	24.2
Titanium A-110AT	24.5	43.9	40.0
Nylon Cloth	18.7	28.1	21.7
Aluminum 2024-T3	29.5	17.6	17.6
Polymethyl methacrylate	35.7	24.1	23.8

DISCUSSION

The results of the three composite systems presented show that the V_{50} ballistic limits of armor can be increased beyond that which can be expected of single materials. In one case, it was demonstrated that one component, glass (usually regarded as a poor armor material), when combined with an excellent armor material (nylon fabric), becomes equivalent in performance to the excellent material. Polymethyl methacrylate and polyvinyl butyral, both inferior in missile-stopping ability, when combined, produce good transparent armor. When two good armor materials, titanium and nylon cloth, are combined, the resulting composite is superior in protective characteristics to any known armor material (based on a calculated V_{50} ballistic resistance limit for titanium A-110AT).

Of the three composites tested, only one, the polymethyl methacrylate/polyvinyl butyral composite, had a V_{50} ballistic resistance limit substantially greater (fifty per cent) than the V_{50} limit of either component on an equal areal density basis. The surprising effectiveness of this composite cannot be completely explained in terms of its components. Although the polymethyl methacrylate is effective in retarding missiles, the rear component, polyvinyl butyral, has a very low V_{50} ballistic limit for its areal density. Thus, although this example does demonstrate that composites are better than single materials, it is an exception to the supposition that the <u>rear</u> component of such composites must be a material of high stopping power. Also, apparently, missile deformation is not required for composites to be more effective than their components.

The other two composites have V_{50} ballistic resistance limits not much different from that of the better component but substantially greater than the other component. The glass-nylon composite has a V_{50} limit double that of glass but very slightly less than that of nylon cloth on an equal areal density basis. Comparison of the residual velocity-striking velocity curves (Figures 2 and 4) for 3/32-inch glass and nylon cloth shows that the difference between the two materials at the V_{50} limit of the composite (approximately 1800 feet/second) is very small (less than 50 feet/second), with nylon cloth having the higher value. Therefore, it would not be reasonable in this case to expect the composite to be distinctly superior to the better component. This composite demonstrates, however, that a material with low stopping power, but effective as a retarding material, can be substituted for a portion of an armor material with a high V_{50} limit to form a composite providing equivalent protection.

The titanium A-110AT and nylon cloth composite has a V_{50} limit somewhat greater than either nylon cloth (by 156 feet/second) or the titanium alloy (by an estimated 81 feet/second) on an equal areal density basis. Comparison of the residual velocity-striking curves for the two materials shows that, for the velocity range explored, the titanium alloy is more effective in reducing the missile velocity than is nylon fabric. However, an extrapolation of the curves to lower velocities indicates that the difference between the two diminishes rapidly and eventually nylon is superior. Considering the composite to be formed by substituting titanium for the front portion of armor consisting of nylon cloth, it is reasonable to expect the composite to be distinctly superior to the nylon cloth (the test results confirm this). When the composite is considered to be formed by substituting nylon cloth for the rear portion of the titanium, it is reasonable to expect the composite to be equivalent or slightly superior to the titanium alloy: again, the results confirm this expectation.

Missile deformation is apparently not required for synergism to occur, although it may play a role in some composite systems. Missile deformation did not occur in the case of the composite with the largest synergistic effect, namely polymethyl methacrylate-polyvinyl butyral.

Since the components, their combinations, and the relative areal densities of the components and total composite areal density were arbitrarily chosen or determined by the availability of the materials, it is reasonable to expect that more effective combinations can be designed within the practical areal density range for personnel armor (10 to 40 oz /sq ft).

Since a V_{50} limit of approximately 1800 ft /sec has already been attained by a composite whose areal density is equal to that of the M-1 helmet and liner (36.9 oz /sq ft.), a V_{50} limit of at least 2000 ft./sec. (for the .22 caliber T37 fragment simulator) for a properly designed composite helmet does not seem unreasonable. Such a future helmet will be capable of protecting against missiles with four times the kinetic energy of missiles than can be defeated by the present standard helmet. Although V_{50} limits are not readily translatable in terms of reduction in battlefield casualties, it appears reasonable to consider such an increase in V_{50} limit should be highly important.

Likewise, for body armor, at an areal density of 20 oz /sq ft , it appears feasible to increase the V_{50} limit of the armor vest from the present 1250 ft /sec to 1500 ft /sec.

Protection for the infantry soldier against small arms fire, although not imminent at this time will become practical if another fifty per cent decrease in weight can be attained. The first fifty per cent decrease in weight was made possible in 1945(2) by the use of a glass-Doron composite as compared to a single material. At present, as indicated by exploratory experiments at this Center, protection against the .30 caliber ball ammunition at a 400 to 500 yard range can be obtained by a 7 lb /sq ft composite armor. This armor appears practical for certain applications where the armor is not worn by the soldier, such as for armoring specific areas of Army aircraft, e.g., seats for the protection of personnel. Composites may be even more effective at much higher areal densities to provide protection against heavier and higher velocity missiles; the results obtained for glass indicate its increasing effectiveness at higher velocities and its greater velocity loss/areal density ratio at higher areal densities. Such armor may be practical for stationary structures or for powered vehicles.

CONCLUSIONS

The belief that the efficiency of a material for personnel armor is expressed by a V_{50} ballistic resistance limit or other measure of its missile stopping power is only partially correct. The stopping power of the complete armor may indeed be the criterion for armor considered as a whole*; but, for component materials of composite armor, both the V_{50} ballistic resistance limit (stopping power) and the missile velocity loss (retardation effect) need be considered in any evaluation or selection. Although materials such as glass have very low stopping power, they are capable, nevertheless, of reducing significantly the energy of the penetrating missile. High energy absorbers, as a class of materials distinct from materials of high stopping power, have been almost completely overlooked in the search for personnel armor materials. Materials of high stopping power, such as nylon cloth, tested above their ballistic resistance limit, offer less resistance, i.e., slow down the missile less than the high energy absorption type of material. It is conceded that materials may exist which have a high ballistic resistance limit as well as good missile-retarding characteristics.

Properly selected combinations of high energy absorbing materials with high stopping power materials are more effective than either component of equivalent areal density. Practical guides to the selection of components are the V_{50} ballistic resistance limit (or equivalent) and the relationship between missile striking velocity and residual velocity. Arrangement of two components into a composite is determined by placing the more effective missile retarding component in front of the more effective missile stopping component.

*Neglecting any decrease in the severity of wounds as a result of armor reducing the velocity of missiles.

SUMMARY

The energy absorption characteristics of glass previously reported by Mellecker and Gailus[3] have been verified for the .22 caliber 17 grain T37 test fragment simulator. Unusual missile-retarding characteristics were also observed for titanium A-110AT and for polymethyl methacrylate sheet.

A significant synergistic effect was noted when a material with high stopping power was combined with a material of high energy absorption. Three composite structures--a glass-nylon cloth, a titanium-nylon cloth and a polymethyl methacrylate-polyvinyl butyral laminate--were found to be equivalent or superior in protective characteristics to an equivalent weight per unit area of any component.

A composite structure of titanium and nylon cloth was found to be superior in protective characteristics to any known armor material (for the .22 caliber 17 grain T37 fragment simulator in the areal density range tested).

A method of selecting components for a synergistic composite that is superior in protective characteristics to any single component was suggested by the use of ballistic limits data and missile residual velocity data.

FUTURE WORK

The exploratory investigation just described has demonstrated that materials do differ in their ability to slow down missiles passing through them as well as in the ability to stop missiles. Composites of dissimilar components properly selected and positioned have a higher ballistic resistance limit (V_{50}) than a component of areal density equal to that of the composite.

Since composites appear to offer the possibility of significantly increasing the protection afforded combat personnel against battlefield missiles, the QM R&E Center Laboratories are conducting an extensive investigation of materials to determine ballistic resistance limits and energy absorption data (missile striking velocity vs residual velocity). These data should be useful in the selection and proper positioning of components. The materials selected for study will include those materials not usually considered suitable for armor since (a) good energy absorbing materials apparently need not by themselves be good absorbers and (b) the immediate purpose of the investigation is to obtain fundamental information concerning materials that may lead to significantly superior armor rather than to a trial and error design of a practical armor system. Specific classes of materials selected are metals, textiles, plastics, glasses and ceramics. In order to determine clearly the relationship between the missile stopping and retarding characteristics of component materials and their composites, the composites will be evaluated concurrently with single materials.

The QM R&E Center program will consider factors such as material weight (areal density), size and type of missile, and missile striking velocity. The areal density will be in the range considered suitable for personnel armor, viz. 10 to 40 oz /sq ft Testing will be conducted with the following missiles: .22, .15 and .10 caliber fragment simulating projectiles, flechettes and other missiles of unusual size or form. Data will be obtained over the range of missile striking velocities from just above the ballistic resistance limit of the material to approximately 4000 ft./sec.

REFERENCES

1. Rogers, M. M. "Two Problems in the Penetration of Thin Sheets of Unbonded Nylon, by the Energy Dissipation Method" Technical Note No. 1-55-P2, Department of Physics, U. of South Carolina, Columbia, S. C., December 1954.

2. Webster, A. P. "Diphasic Armor 1. Glass Doron; Status Report" Research Division, Bureau of Medicine and Surgery, Navy Department, Washington, D. C., 21 July 1945.

3. Mellecker, J. B. and W. J. Gailus, "The Light Armor Testing Laboratory and Research Relating Thereto" Final Report on QMC 30-F Vol. II, Contract No. W44-109-qm-305, 31 Oct. 1944 to 15 Dec. 1945.

4. The Development of Equipment and Methods for Studying the Dynamics of the Performance of Light Armor Consisting of Fibrous or a Combination of Fibrous and Metallic Materials, Final Report, Contract W23-072-ord-2128, Midwest Research Institute, Kansas City, Mo., November 15, 1948.

5. Design Manual for Personnel Armor, Contract No. DA23-072-ord-9, Midwest Research Institute, Kansas City, Mo., February 15, 1951.

6. The Development of Laminated Armor, Final Report, Contract W-33-019-ord-6266, Battelle Memorial Institute, Columbus, Ohio, September 27, 1948.

7. Porter, W. R. and J. J. Dunn, Jr., A Ballistic Evaluation of Nylon and Doron Body Armors, Ballistic Research Laboratories Report No. 844, Aberdeen Proving Ground, Maryland, December 1952.

8. Weinberger, J. V. and H. A. Delcellier, "Ballistic Resistance of Textiles," presented at 4th Commonwealth Defence Conference in Clothing and General Stores, London, 1953.

9. Weiner, L. I., "Observation of Failures Noted in Nylon Fabrics Penetrated by Missiles and the Influence of Shear and Slippage of Yarns on Fabric Behavior," presented at Meeting of National Research Council, Committee on Fabrics for Body Armor, Washington, D. C., 7 October 1953.

10. Specification MIL-A-12370B(QMC) Armor, Body, Fragmentation Protective, M1952A, dated 1 February 1955.

11. Specification MIL-A-12369(A)(QMC) Cloth, Nylon for Armor, dated 31 January 1955.

12. "Operating Procedure for the Ballistic Acceptance Testing of Vest, Armor M52-3A and Similar Materiel with Projectile, Fragment Simulator Caliber .22 T37," Development and Proof Service, Aberdeen Proving Ground, Maryland, dated 1 April 1953.

13. Stewart, G. M., D. R. Petterson and T. Hamburger, "Dynamics of Body Armor Materials under High Speed Impact. Part II. Single and Triple Microflash Instrumentation for Single Yarn Studies," CWLR 2142, US Army Chemical Warfare Laboratories, Army Chemical Center, Md., 29 July 1957.

14. Alesi, A. L., E. J. Greene and A. S. Tente, Investigation of Ballistic Protective Materials for Personnel Armor, Progress Report 1: QMRE 14, Energy Absorption and Ballistic Resistance Limits (V_{50}) of Armor Materials when Perforated by a Fragment Simulating Projectile (.22 Caliber T37)., QM R&E Command, Natick, Mass., December 1957.

15. Armor Test Report No. AD-1190, "Report on a Test of Personnel Armor Materials with Fragment Simulating Projectiles," Development and Proof Service, Aberdeen Proving Ground, Maryland, 26 February 1954.

16. Caplan, J., "Body Armor Development Test," Textile Engineering Laboratory Materials Examination Report 2365, Quartermaster R&E Command, Natick, Mass., 4 November 1953.

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